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Modelling of Thin Layer Drying Kinetics of Tomato (*Lycopersicon esculentum* Mill) Slices under Direct Sun and Air Assisted Solar Dryer

Oyerinde. A.S.

Abstract— **Drying experiments were conducted using direct sun drying and indirect passive solar dryer to simulate the drying processes of tomato slices, Tomato slices of 3mm thickness were placed on perforated stainless steel trays in a thin layer and dried to equilibrium moisture content. All samples were dried from an initial moisture content of 95.4 %wb to 10.2 %wb for sun dried samples and 8.5 %wb for solar dried samples. The drying data were fitted with ten published thin layer drying models. Selection of the best model was achieved by comparing the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) between the experimental and predicted values. The diffusion coefficient and activation energy were determined using the Arrhenius equation. The results showed that the Page model was found to best describe both the sun and solar drying kinetics of tomato slices under the conditions tested. Effective moisture diffusivity was $5.07\times10^{-7}m^2/s$ for sun dried and $2.32\times10^{-7}m^2/s$ for solar dried tomato samples, while activation energy ranged from 32.38 to 33.53 kJ/mol for sun dried and 39.14 to 42.12kJ/mol for solar dried samples, respectively. It was concluded that the Page model is applicable to predict moisture content of tomato slices during direct sun and solar drying of tomato slices.**

Index Terms—**Mathematical modeling, Solar drying, Sun drying, Tomato slices.**

I. INTRODUCTION

Tomato is the edible fruit of the *Solanum lycopersicum* plant, believed to have originated from the Andes mountains region of South America [1]. It is widely consumed raw, in soups, sauces and stews [2], and accounts for at least 18% of daily vegetable consumption in Nigeria [3].

Spoilage of fruits and vegetables is a major problem in Africa and many parts of the world. It is estimated that no less than 40% of harvested tomatoes in Nigeria are lost to spoilage [4], [5]. *Penicillium notatum, Mucor spp.* and *Bacillus subtilis* have been identified as some of the leading micro-organisms responsible for post-harvest spoilage of tomato [6], [7]. Spoilage is inevitable without preservative measures, but is accelerated by bruises and other injuries to tomato fruits sustained during tomato handling operations, particularly during harvesting, packaging and transportation [8], [9]. Bruises result in rapid moisture loss, and the consequent shrivelled tomatoes have reduced market value [10]. These problems have prompted a lot of research into methods of tomato preservation and storage. Most stored tomato is available as various tomato paste products, notably tomato puree (tinned) and tomato ketchup (usually bottled). The ketchup is often sugared and may be used directly on food, while the puree is unflavoured and is often used during cooking. The production and packaging processes for both are however expensive, well out of reach of the average tomato farmer or marketer, and so other methods are being explored.

Freezing and dehydration have been noted to be less expensive methods of preserving fruits and vegetables. Drying, particularly solar drying, is especially suitable for developing countries which have problems with power supply [11]. Solar drying offers a highly effective and practical means of preserving fruits and vegetables, reducing postharvest losses and also reducing shortages in their supply.

The most common methods of drying of agricultural materials are by direct sunlight, the use of solar dryer, and the use of mechanical dryers. Sun drying is easy and cheap to carry out, but exposes the materials to weather elements (precipitation and wind), dirt, and consumption by animals, which often results in a product of low quality. Solar drying of agricultural materials in enclosed, air-assisted solar dryers is an important way of reducing post-harvest losses and poor quality of dried materials associated with open sun-drying methods [12]. In rural areas of most developing countries (where agricultural activities are predominant), electricity is unavailable, unreliable or too expensive, solar dryers therefore appear to be the best means of drying agricultural materials [13].

The drying process may be described using thin layer drying models as mathematical models are used to estimate the drying time and moisture content of a given agricultural material at any time after they are subjected to known drying conditions [14].

The main objective of this study is to investigate the effect of drying methods on drying characteristics of tomato and to evaluate the ability of some mathematical models to predict the drying behaviour of tomatoes dried using open sun and solar dryer.

II. MATERIALS AND METHODS

Fresh plum tomatoes were purchased from Owode-Owena market, Akure, Nigeria. They were thoroughly washed in potable water, after which defective ones were separated. Batches of two kilogram tomatoes (2kg) each were then separated and sliced lengthwise to approximately 3mm thickness using sharp stainless steel knives. Sliced tomatoes were arranged on perforated stainless steel sheets for thin layer drying. Tomatoes for each drying method were arranged on four (4) trays with approximately 500g per tray, making a total of about 2kg per batch. Initial and final moisture contents were determined by drying a fresh sample in an oven at 105°C

Dr. Oyerinde, A.S. Agricultural and Environmental Engineering Department, Federal University of Technology, Akure, Nigeria.

for 3 hours [15]. Thereafter, moisture content was determined according to [15] in (1):

$$MC = \frac{W_1 - W_2}{W_1} \quad (1)$$

where:
MC = moisture content, % wet basis
W_1 = weight of sample before drying, g
W_2 = weight of sample after drying, g.

The first batch was dried under direct sunlight while, the second batch was dried simultaneously in an air assisted, indirect, stainless steel cabinet solar drier. For each drying method, a tray was marked and withdrawn at one-hour intervals to determine the weight. This was done until no further weight change was noted. With the initial moisture content known, moisture content at a particular weight during drying could be determined because the dry matter content of any sample remains constant during drying, and can therefore be used as a reference point. Moisture content M_2 at weight W_2 during drying was thus determined from the following relationship according to [16], as shown in (2):

$$M_2 = \frac{100(W_2 - W_1) + W_1 M_1}{W_2} \quad (2)$$

where:
M_2 = moisture content of material of weight W_2 (g) during drying, % wet basis
W_1 = weight of material before commencement of drying, g
M_1 = initial moisture content (IMC) of material (ie, moisture content of material before commencement of drying), % wet basis.

Moisture ratio was also determined by (3) according to [17]:

$$MR = \frac{M - M_e}{M_o - M_e} \quad (3)$$

where:
MR = moisture ratio
M = moisture content at time t, % wet basis
M_e = equilibrium moisture content, % wet basis
M_o = initial moisture content of material being dried, % wet basis.

For each drying method, the moisture ratio (MR) data obtained were fitted to ten different moisture ratio models to select a suitable model for describing the drying process of tomato slices. The models used are semi-theoretical and empirical models found in literature. Semi-theoretical models are based on Fick's second law, but are simplified with empirical coefficients added in some cases in order to improve curve fitting [18]. In empirical models, there is a direct relationship between moisture content and drying time. The models used are presented in Table 1.

In these models, the moisture ratio (MR) is defined as given in (3). Three statistical parameters: the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) were used as the criteria for selecting the best model. The reduced chi-square and root mean square error were obtained as given in (14) and (15) according to [18] as:

$$\chi = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pred,i}\right)^2}{N - z} \quad (14)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pred,i} - MR_{\exp,i}\right)^2\right]^{\frac{1}{2}} \quad (15)$$

where:
χ^2 = chi-square
$RMSE$ = root mean square error
N = number of observations
z = number of model constants
$MR_{exp,i}$ = ith experimental data
$MR_{pred,i}$ = ith predicted data.

In general, the higher the R^2 values and the lower the χ^2 and RMSE values indicated that the model is best fitted. Non-linear regression analysis was performed using Microsoft® Excel Solver to determine the models parameters.

The drying characteristics of agricultural materials can be described using Fick's diffusion equation [19]. The solution of Fick's law for a slab is given in (16), according to [24]:

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (16)$$

where:
MR = moisture ratio
M = moisture content at time t, % wet basis
M_e = equilibrium moisture content, % wet basis
M_o = initial moisture content of material being dried, % wet basis
D_{eff} = effective moisture diffusivity (m^2/s)
t = drying time (hours)
L = thickness of slice of sample (m).

For long drying periods, (16) can be further simplified by using only the first term of the series. Thus, (16) is written in a logarithmic form as (17), where K_0 is the slope of the graph of the natural logarithm of the moisture ratio, InMR, versus time, t [25]:

$$K_o = \frac{\pi^2 D_{eff}}{4L^2} \quad (17)$$

The relationship between effective moisture diffusivity values and drying temperature can be calculated using the Arrhenius equation [20]:

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \quad (18)$$

where:
D_0 = the pre-exponential factor of the Arrhenius equation (m^2/s)
E_a = activation energy for water diffusion (J/mol)
R = constant of perfect gases (8.314J/molK)
T = air drying temperature (K).

Table 1: Thin-layer empirical and theoretical drying models used for mathematical modelling

Drying Parameters	Sun drying	Solar dryer

Initial moisture content (%wb)	95.4	95.4
Equilibrium moisture content (%wb)	10.16	8.47
Drying temperature (^{0}C)	22-32.5	35-58.5
Drying time (Hrs)	15	20
Activation energy (KJ/mol)	32.28-33.53	39.14-42.12
Moisture diffusivity (m^2/s)	$5.07x10^{-7}$	$5.07x10^{-7}$
Crude protein (%)	21.78±0.02	28.41±0.24
Lycopen and vitamin C (mg/100g)	18.05±0.19	14.62±0.04

Table 2: Thin-layer empirical and theoretical drying models used for mathematical modelling

S/N.	Model name	Model equation	Equation number	Reference
1	Newton	MR = exp(-kt)	(4)	[19]
2	Page	MR = exp(-kt^n)	(5)	[17]
3	Henderson & Pabis	MR = aexp(-kt)	(6)	[20]
4	Logarithmic	MR = aexp(-kt)+c	(7)	[19]
5	Two-term	MR = aexp(-kt)+cexp(-gt)	(8)	[18]
6	Midili-Kucuk	MR = aexp(-kt^n)+bt	(9)	[21]
7	Modified Page	MR = exp(-kt)^n	(10)	[22]
8	Two-term Exponential	MR = aexp(-kt)+(1-a)exp(-kat)	(11)	[23]
9	Diffusion Approach	MR = aexp(-kt)+(1-a)exp(-kgt)	(12)	[18]
10	Parabolic	MR = a+bt+ct^2	(13)	[24]

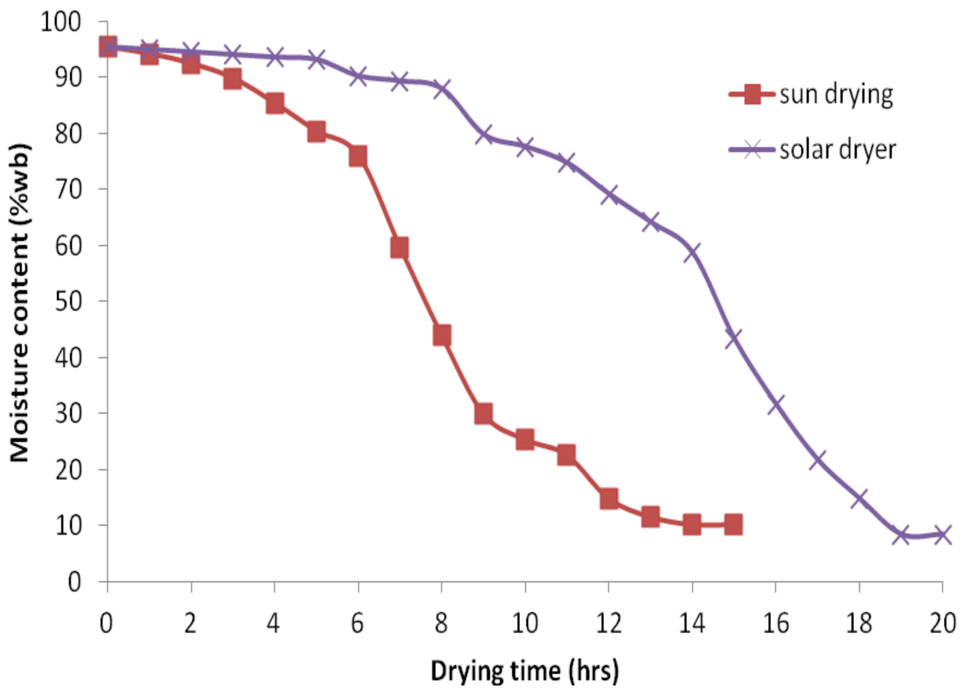

Figure 1: Moisture content with time using the 2 drying systems in drying of tomato slices

D_0 is obtained by plotting the natural logarithm of effective moisture diffusivity, $\ln D_{eff}$, values, obtained for various values of *MR* from (16), against the inverse of temperature (1/T).

III. RESULTS AND DISCUSSION

A. Drying Conditions

Ambient temperature (dry bulb) varied from 22.0 ^oC – 32.5^oC and relative humidity from 70.8 % – 97.0 %, while solar radiation varied from 231.14 W/m^2 – 912.41W/m^2 during the drying period. Within the solar dryer, dry bulb temperature and relative humidity varied from 35.0 ^oC – 58.5 ^oC and 38.0 %– 85.0 %, respectively as shown in table 1. Other drying parameters were also shown for the two drying systems that were employed

B. Drying Characteristics

Moisture content and moisture ratio were found to decrease with drying time for both sun dried and solar dried samples as shown in figure 1. This is in agreement with results from [19], [24] and [20]. From an initial moisture content of 95.4% wet basis, sun dried samples were dried to 10.2% wet basis. Drying time was 15 hours over a period of 3 days. Drying rate generally decreased with drying time, with increased drying rate observed between the first and second days during overnight storage. From an initial moisture content of 95.4% wet basis, solar dried samples were dried to 8.5% wet basis. Drying time was 20 hours over a period of 4 days. Drying rate generally decreased with drying time, with increased drying rate observed between the first and second, as well as the second and third days during overnight storage.

C. Mathematica Modelling

From the ten models used, the Page model (with R^2 = 0.994) was found to best predict the sun drying of tomato slices under the given temperature and relative humidity conditions. The Page model (R^2 = 0.946 – 0.983 for various slice thicknesses) was also found by [17] to best predict the sun drying of tomato slices. Table 2 shows the ten drying models used, the adjusted constants, the values of R^2, χ^2 and RMSE, and the ranking for each model, for sun drying data.

For the solar dryer, the Page model (with R^2 = 0.989) also was found to best predict the solar drying of tomato slices under the given temperature and relative humidity conditions. The Page model (R^2 = 0.983 – 0.987 for various slice thicknesses) was also found by [17] to best predict the solar drying of tomato slices. Tables 3 and 4 shows the ten drying models used, the adjusted constants, the values of R^2, χ^2 and RMSE, and the ranking for each model, for solar drying.

D. Effective Moisture Diffusivity and Activation Energy

The effective moisture diffusivity was 5.07×10^{-7} m^2/s for sun dried samples and 2.32×10^{-7} m^2/s for solar dried samples. Reference [17] reported a moisture diffusivity range of 3.09 m^2/s to 9.28×10^{-9} m^2/s for sun drying and 4.25 m^2/s to 7.67×10^{-7} m^2/s for solar drying, for tomato slice thicknesses ranging from 4 to 8mm. Reference [19] also reported a range of 3.42 m^2/s to 8.69×10^{-9} m^2/s for sun drying and 5.25 m^2/s to 13.66×10^{-9} m^2/s for solar drying, for tomato slice thicknesses ranging from 3 to 7mm. While [20] obtained moisture diffusivities ranging from 3.07 m^2/s to 5.70×10^{-9} m^2/s for tomato slices of 1cm thickness dried in a hot air dryer at temperatures ranging from 38 ^oC to 50 ^oC. Higher values of effective moisture diffusivity obtained in this study might be due to differences in tomato variety and slice thickness. The obtained values are however in the range of 10^{-11} m^2/s to 10^{-9} m^2/s as specified by [26].

Activation energy ranged from 32.38 kJ/mol to 33.53 kJ/mol for sun dried and 39.14 kJ/mol to 42.12 kJ/mol for solar dried samples, respectively. Activation energy for tomato slices dried at temperatures ranging from 30 ^oC to 50^oC varied from 46.81 kJ/mol to 52.61kJ/mol during hot air drying as reported by [25]. Drying tomato slices at temperatures ranging from 38 ^oC to 64 ^oC, [20] reported an activation energy range of 10.67 kJ/mol to 13.56kJ/mol.

IV. CONCLUSION

The drying behavior of tomato slices during direct sun drying and usage of air assisted solar dryer were investigated. It took 15 drying hours for sun dried samples to reach equilibrium moisture content of 10.2 %, while the solar dryer took 20 hours to reach the equilibrium moisture content of 8.5 %. To explain the drying characteristics of tomatoes slices, ten semi-theoretical and empirical models found in literature were applied and fitted to the experimental data. From the statistical analysis, it was concluded that the Page model best predicted the drying data for both sun and solar dried samples.

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Dr. A.S. Oyerinde is a Senior Lecturer with specialization in Post Harvest Technology in the Agricultural and Environmental Engineering Department, Federal University of Technology, Akure, Nigeria. He is a member of the Nigeria Institution of Agricultural Engineers as well as the Nigerian Society of Engineers. He has over 10 scholarly articles in refereed journals and conference proceedings

Table 3: Model constants, statistical parameters and ranking for sun drying data

Model	Constants	R^2	χ^2	RMSE	Ranking
Newton	k = 0.11546	0.883	0.0346	0.045	7
Page	k = 0.00116 n = 3.17766	0.994	0.0009422	0.000824	1
Henderson & Pabis	a = 1.227675 k = 0.141518	0.855	0.0276726	0.024214	10
Logarithmic	a = 1.227674 k = 0.141518 c = 0	0.855	0.0298013	0.024214	6
Two-term	a = 0.069980 k = 0.141526 c = 1.157667 g = 0.141518	0.855	0.0322847	0.024214	4
Midili-Kucuk	a = 0.987386 k = 0.000993 n = 3.238964 b = 0	0.995	0.0008837	0.000773	7
Modified Page	k = 0.096953 n = 1.190907	0.883	0.0370813	0.032446	2
Two-term Exponential	a = 0.000314 k = 366.7126	0.883	0.0371087	0.03247	9
Diffusion Approach	a = 44.82723 k = 0.001601 g = 0	0.946	0.0151304	0.012293	3
Parabolic	a = 1.117741 b = -0.08206 c = -5.6×10^{-5}	0.946	0.0101222	0.008224	5

Table 4: Model constants, statistical parameters and ranking for solar drying data

Model	Constants	R^2	χ^2	RMSE	Ranking
Newton	k = 0.05124	0.780	0.0446353	0.04251	7
Page	k = 0.00001 n = 4.372923	0.989	0.0017589	0.001591	1
Henderson & Pabis	a = 1.22573 k = 0.068137	0.744	0.03635382	0.032892	8
Logarithmic	a = 70.92067 k = 0.000755 c = -69.7017	0.876	0.0179011	0.015344	5
Two-term	a = -10.98095 k = -0.050004 c = 12.00545 g = -0.04532	0.981	0.0028976	0.002346	3
Midili-Kucuk	a = 1.24608 b = -0.04809 k = 0.121941 n = -0.015744	0.885	0.02182739	0.01767	6
Modified Page	k = 0.05393 n = 0.950232	0.780	0.0469845	0.04251	9
Two-term Exponential	a = 0.06246 k = 0.729805	0.758	0.0530722	0.048018	10
Diffusion Approach	a = 1.06495 g = -53.076 k = 0.002707	0.973	0.0044182	0.003787	4
Parabolic	a = 0.98336 b = 0.016252 c = -0.00354	0.985	0.0020702	0.001774	2

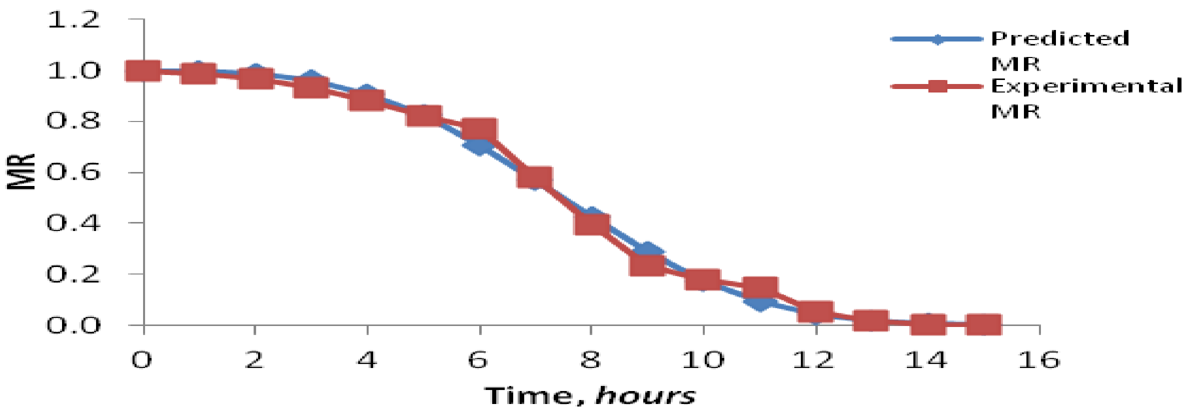

Figure 2: Experimental versus Page-predicted moisture ratio with time for sun drying of tomato samples

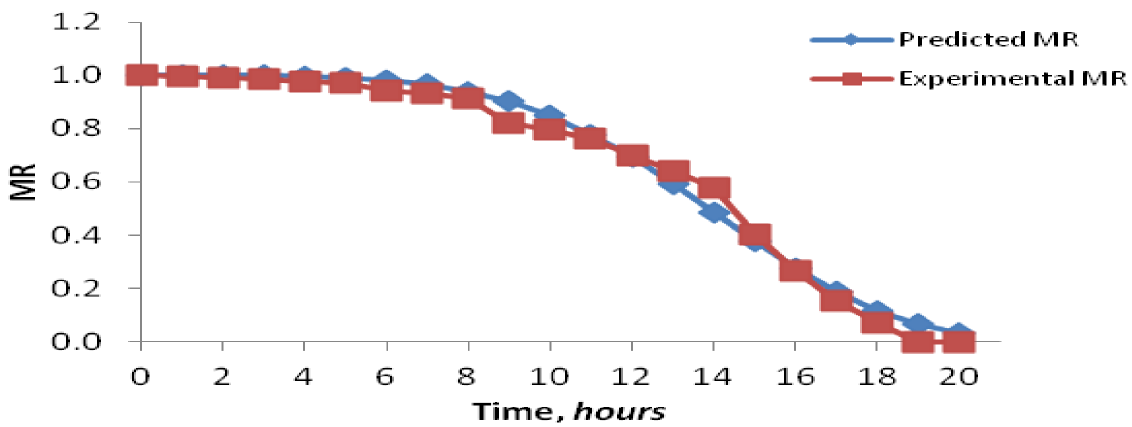

Figure 3: Experimental versus Page-predicted moisture ratio with time for solar drying of tomato samples